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THE THERMIONIC VALVE IN SCIENTIFIC RESEARCH.*

BY

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The Thermionic Valve, which as a technical invention has made possible the great achievements of telephonic broadcasting and television, arose out of scientific research intended to elucidate certain observed phenomena in connection with the working of incandescent electric lamps in 1882 and 1883. It has also provided in itself a new and valuable instrument of research for the physical investigator. The initial steps were taken in this invention when the writer as Scientific Adviser of the Original Edison Electric Light Company of London began to study the projection of carbon atoms from the carbon filament of the then used Edison carbonized bamboo filament electric lamps, which, together with the carbonized cotton thread incandescent lamps of Swan, provided the first practical domestic electric lighting system for general use. It was soon found that these lamps had a black deposit made on the interior of the glass bulb in course of

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time which was fairly uniform and was doubtless due to an evaporation of the carbon, which substance like iodine and camphor and some others passes from the solid state to the gaseous without any intermediate liquid state.

On the other hand in certain cases in which a line of no carbon deposit appeared on the bulb in the plane of the hairpin-shaped carbon filament, it was evident that the projection of carbon particles had taken place from one particular overheated point on the filament. This projection was due to a process of electric "spluttering" which was also the cause of a green copper deposit on the bulb in some cases, since in the Edison lamps the ends of the carbon filament were well connected to the platinum leading-in wires by an electrodeposit of copper over the clamp. This carbon sputtering then clearly took place along straight lines by reason of electric repulsion of carbon ions carrying an electric charge.

Edison had noticed in 1883, that when a metal plate carried on a wire was sealed through the bulb of his carbon filament lamp and connected externally to the lamp by a circuit joined to one or other terminal of the filament, an electric current flowed in this circuit if it terminated on the positive terminal of the lamp filament which was heated by a direct voltage but little or no current when the current terminated on the negative terminal of the filament. The author of this paper made an extensive investigation of the cause of this effect which Edison had not explained or utilized. This was published in 1896 in the *Proceedings of the Physical Society of London* and in the *Philosophical Magazine* for July 1896.

In this paper an extensive set of experiments was described which proved that certain particles charged with negative electricity were being ejected from the incandescent filament of carbon or from metal wires raised to incandescence in an evacuated bulb. It was at first assumed that these carriers were atoms or ions of carbon. It was proved that they were material particles of some kind, but it was not until four or five years later that Sir Joseph Thomson showed that they were the particles of ultra-atomic size we now call electrons.

Amongst the experiments described was one in which a grid formed the positively charged anode plate by which the electrons shot off from the filament were collected.

It was then proved in the above mentioned paper that if a highly evacuated glass bulb had in it one hot carbon and one cold metal electrode the space between had a unilateral electric conductivity and could convey negative electricity from the hot cathode to the cold anode but not in the opposite direction. A large variety of experiments supported this conclusion.

No additional uses or practical application of this fact was made until after the advent of electromagnetic wave telegraphy, when it became evident that it would be necessary to replace the capricious and easily disturbed coherer by some more certain device as a detector of the feeble high frequency electric currents or voltages induced in the receiving aerials of wireless telegraph apparatus.

The writer then made in November 1904 the type of rectifying electronic valve since associated with his name which converted these small alternating currents into direct currents which could be detected by galvanometers or telephone receivers and thus made signal-detecting instruments in this system of wireless telegraphy. It consisted of a carbon-filament vacuum lamp having a metal cylinder round the filament, the said cylinder being carried on a wire sealed through the wall of the glass bulb.

This Fleming rectifying valve came immediately into extensive use by Marconi's Wireless Telegraph Company in England as a practical wireless detector. It preceded by two years the invention of the first crystal rectifying detector of H. H. C. Dunwoody, namely the carborundum crystal detector patented in the United States in 1906, No. 837,616, or British patent No. 5332 of 1907.

It is frequently stated that the early Fleming Valves were merely low vacuum, or as we should now say, soft valves. This however is quite incorrect. In the writer's British Specification No. 24,850 of 1904 or U. S. A. Specification No. 803,684 of 1905 it is clearly stated that a high vacuum is to be made in the bulb and as a matter of fact some of the earliest valves made were exhausted by the use of the beautiful

process of Sir James Dewar in which the high vacuum is made by the absorptive power for gases of cocoanut charcoal cooled with liquid air.

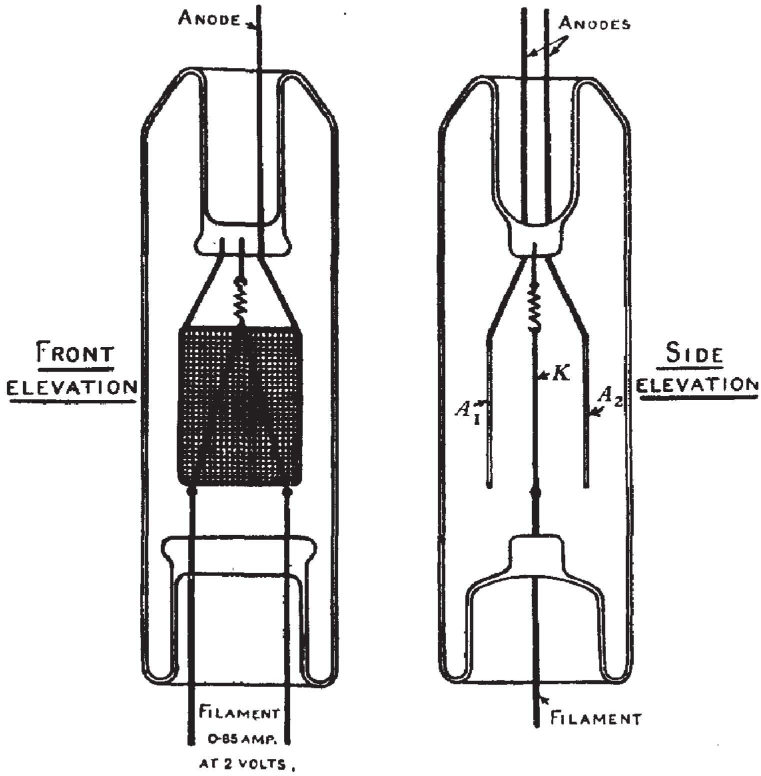
In this case the electric current in the valve is wholly conveyed by electrons emitted by the incandescent filament and not by ionisation of residual gas atoms in the bulb. It was not then a subsequent invention to create what is now called a "hard" valve. Some of the earliest experimental thermionic valves were quite hard. The writer also showed that by the use of two such rectifying valves both phases of an alternating current could be rectified or converted to direct currents. The addition of the "grid" between the "plate" or anode and the incandescent filament which converts the rectifying valve into an amplifying valve was first described by Lee de Forest in his British patent specification No. 1427 of 1908, dating however under the convention as from January 29, 1907.

But the strange thing is that this British patent for an important improvement was allowed to lapse in 1911, whereas it could have been maintained for fourteen years from the date of application in England by payment of fees. It would however be foreign to the purpose of this short paper to enter into any description of the many various important modifications of these two and three electrode thermionic valves for technical purposes in radio-working, as the immediate object here is to mention the applications of them in pure scientific research.

One of those made by the writer in 1931 comprised the use of a valve having a single hairpin-shaped filament of thoriated tungsten, commonly called a dull emitter filament, placed between two equal and equidistant grid wire anodes on either side. These grid anodes were of rectangular shape and formed of 18 vertical fine wires, and 27 horizontal wires interlaced so as to form a network anode of fine wires, the anode area being 9 centimetres square. Each anode was one centimetre distant from the filament. (See Fig. 1.) The filament was rendered scarcely incandescent by 2 volts, E.M.F. from a single cell accumulator.

The two grid anodes were connected with the filament through equal resistances with the two coils of a sensitive

FIG. 1.



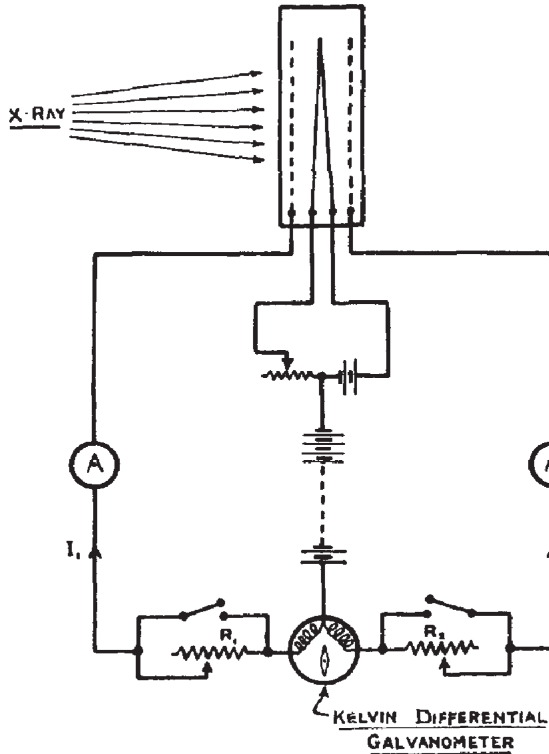
Special two-anode Fleming thermionic valve with dull-emitter filament.

differential galvanometer as shown in Fig. 2, and the common part of the circuit had in it a battery of 4 volts E.M.F. When adjustments of resistance on the two sides were carefully made the galvanometer needle remained at zero when the electron current flowing to each grid was 7.4 microamperes and the potential difference of the filament and each anode was close to 4 volts.

This arrangement proved to be a highly sensitive electroscope. If a stick of ebonite rubbed on the coat sleeve was held on one side of the valve on a line passing perpendicularly through the centre of the two grids, it caused the electrons on one side to be accelerated in their motion to the grid and on the other side to be retarded, and so caused a difference in the two currents and a large deflection of the needle of the differential galvanometer.

One experiment tried with this differential valve was to

FIG. 2.



Arrangement of circuits with two-anode valve for testing the effect of an X-ray beam upon a stream of electrons.

see whether a powerful beam of X-rays propagated with or against a stream of electrons could alter the velocity of that stream. It is well known that all optical phenomena can be divided into two classes. There are those like interference or diffraction which can be perfectly explained on a pure wave theory of light, assuming Maxwell's theory that the fluctuating variables are electric and magnetic forces or fluxes in the plane of the wave front and at right angles to the direction of propagation of it, these vectors being in phase with each other.

Then in contrast with this are phenomena such as the photoelectric effects which seem only explicable on the theory that light consists of photons or quanta of energy of magnitude hv, where h is the so-called Planck's Constant and v is the frequency of that light. The difficulty however is to visualize a quantum of energy. On the other hand an electron

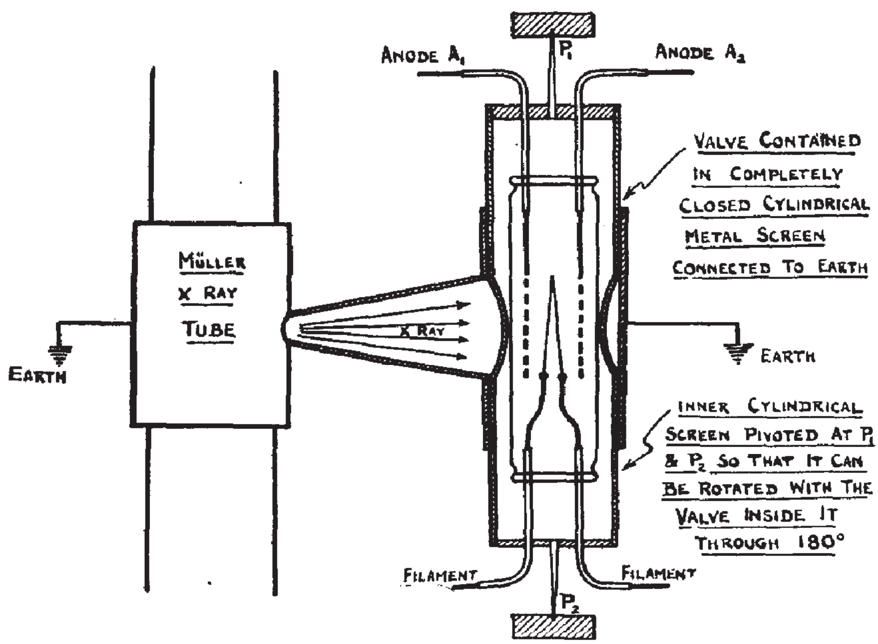
itself gives evidence of possessing a wave-like nature as shown by the experiments of Davison and Germer, described in 1927 and of G. P. Thomson in 1929.

The Compton effect made known in 1923 also proved that photons could rebound from electrons in atoms, the loss of momentum of the photon being represented by the momentum given to the recoiling electron.

If then the energy of light is concentrated in photons or packets each of energy ($h\nu$) and momentum $h\nu/c$, and if the wave-length of an electron of mass m and velocity v is given by h/mv it seemed an interesting experiment to ascertain if a powerful beam of X-rays containing therefore photons of high energy could alter the speed of electrons in a stream flowing with or against the photons.

The above described valve was used enclosed in a brass case with a hole opposite the grid (see Fig. 3). The X-rays

FIG. 3.



Two-anode thermionic valve with earthed metal screen round it.

were provided by a Müller structure X-ray tube with hot cathode actuated with 60,000 volts giving an electron current of 21 milliamperes striking the anode plate of the tube.

This is equivalent to 131×10^{15} electrons emitted per second. If each electron gave rise to a photon on striking the target and thus creating the X-ray beam and if each photon had an energy of 36×10^{-9} erg, since the frequency (which was not accurately measured) would be about 10,000 times that of visible light, the result would be that photons having a total energy of 524 million ergs would impinge on each centimetre square of the grid of the valve per second. On the other hand the electron current of the valve passing from filament to grid is 7.4 microamperes under an E.M.F. of 4 volts in power equal to 296 ergs per second or 33 ergs per centimetre square of the grid per second.

We have assumed as a limiting case that each electron in the X-ray tube striking the target produces one photon. If as a more probable value we take only 10 per cent. as so doing we had then two opposing streams, photons conveying 50 ergs per square centimetre per second and electrons opposing them conveying 33 ergs per square centimetre per second. The result of the experiment was that the incidence of this powerful X-ray beam produced not the smallest disturbance of the electron stream although a variation of 1 part in 2,000 of the electron currents in the valve could have been detected. It cannot be said that this result is inconsistent with the Compton effect because the two cases are different. In the Compton effect the X-rays are scattered by a solid body (? carbon) and the electrons from which the photons rebound are tethered in atoms. But in the case of my valve experiment the electrons are free and somewhat widely spaced apart.

A calculation shows that in 1 centimetre square of cross section of the electron stream to each grid there would be about 1,200 electrons, and in the X-ray beam about 600 photons passing through them. It would appear then that the chances of a collision of photon and electron are very small and all that the above experiment really proves *is* the exceedingly small space occupied by the electrons or photons out of the total volume occupied by any number of them in such streams as here employed. The question how the negative result above mentioned is to be interpreted is conditioned then by suppositions as to the actual nature of

photons and electrons for which we have little or no unquestioned facts. Even assuming that both are some kind of wave the photons can only move at the rate of 3×10^{10} centimetres per second and have no "rest mass." The electron can move at any speed less than 3×10^{10} centimetres per second and has a rest mass equal to its intrinsic energy divided by 9×10^{20}. If the electron is indeed a group of waves we have as yet no explanation why electron repels electron or how a photon can collide with it.

The experiment does suggest however some reconsideration of our ideas as to the nature of electrons and photons. When we speak of an electron as "particle" that immediately raises the question What is this particle made of? And even if we assume the existence of subelectrons we ask What are they made of? and so on. The same for photons often asserted to be the "particles" or "quanta" of energy.

The new quantum theory suggests to us that we must think of electrons as wave groups in a medium and that may involve that the so-called motion of an electron is not a bodily movement of something retaining a constant individuality but the cessation of some kind of wave in one place and its re-creation in another. The photon on the other hand may be regarded simply as a singularity on the wave front of the light, a locality where the amplitude of the light vectors is greater than the average, thus giving as Sir Joseph Thomson called it a "speckled" appearance to the wave front. As the wave passes over atoms it is only at these singularities that the energy is great enough to cause a possible elevation of an orbital electron to an orbit of greater potential energy. For visible light the energy of a photon is about 3×10^{-12} of an erg. For X-rays it may be about 10,000 times greater or of the order of 10^{-8} of an erg. The energy required to remove an electron from a metallic atom may vary from about 2.7 to 6.3 billionths of an erg ($= 6.3 \times 10^{-12}$ erg) and hence to raise it from one orbit to another will require rather less.

We must bear in mind however that the mental pictures we are able to form of physical events are in any case only symbols or hieroglyphics and may bear no more resemblance to the actual event or phenomenon than the written or

printed marks which form what we call a "word" bear to the form of the thing that word denotes.

Our mental pictures are made up necessarily of fragments of past sense impressions and the more easily or clearly we can build up a mental picture of a physical event the less is it likely to be true to fact. In any case it only suffices for a certain limited time and then has to be thrown on one side. Thus the Thomson mental picture of an atom was superseded by that of Bohr and that of Bohr by that of Schroedinger and that in turn by some yet unimagined conception.

We pass on then to mention some other interesting applications of the thermionic valve in scientific research and one of these is due to Dr. R. Whiddington, Cavendish Professor of Physics in the University of Leeds, described in the *Philosophical Magazine* of November 1920. If in a three electrode thermionic valve or triode, as it is often called, we couple inductively by a transformer the grid and the plate or anode circuits, and if the latter includes a capacity inductance closed circuit of low resistance then oscillations of frequency N are set up in this circuit determined by the capacity C and inductance L according to the law.

$$N = 1/2\pi\sqrt{CL}.$$

If the capacity C is provided by a parallel plate condenser the plates each having an area A and interdistance x then the frequency of the oscillations set up is given by

$$N = \sqrt{x/\pi LA}.$$

If a second valve oscillator is set up having a condenser of capacity C^1 which is adjustable, we can arrange that the frequency difference of the two sets of oscillations comes within the audible range and creates "beats." These can be amplified by a valve amplifier and made to actuate a loud speaking telephone so that the beats per minute can be easily counted. If then the capacity C is varied by altering the distance x even by a very minute amount there is a change of beat frequency which can be counted and by which the change in the interdistance x can be measured.

Professor Whiddington found that it was quite possible to

detect a change in x of two to four-thousandths of a millionth of an inch in the interdistance of the flat condenser plates. The plates were normally about one-thousandth of an inch apart.

This apparatus is therefore capable of detecting a movement of the condenser plates to or fro of about 1/1200 of a millionth of an inch which is far less than that of a Whitworth screw micrometer. It could also be used to detect exceedingly small changes in di-electric constant of certain highly insulating liquids.

This invention can be applied in the design of many different instruments as for instance in the construction of a microbalance where the tilt of the balance beam due to a weight is made to alter the distance between two condenser plates.

In a paper by Dr. Whiddington and Mr. F. A. Long in the *Philosophical Magazine* for January 1925, it was shown that it could be employed to estimate a change of weight of 10^9 gram in a load of about 0.2 gram. It would be applicable therefore to the measurement of the displacement of a torsion balance under very small forces such as the measurement of the gravitational constant of matter or the pressure of radiation.

Another very interesting application of the thermionic triode is in the production of electric oscillations of exact frequency controlled by a tuning fork, reed or phonic wheel. This application was originally due to Dr. W. H. Eccles and Mr. Jordan and described by them in a British Patent Specification by W. H. Eccles and F. W. Jordan, No. 155,851 of April 17, 1918 (see also W. H. Eccles, *Proc. Physical Society*, London, Vol. 31, p. 269, 1919). If it is desired to obtain electric oscillations or rather alternating currents of perfectly constant frequency within the limits of audition, it would in general require a very large capacity and inductance in the anode circuit of a thermionic valve with grid and plate circuits coupled as usual in the retroactive use of the valve for the production of such an alternating current. The frequency in any case is not entirely independent of the resistance of the circuits by heating. Hence it is difficult to preserve an absolute constancy in the fre-

quency. Yet for certain purposes in telephonic research on the calibration of electric-wave meters an absolute or high degree of constancy may be essential. Dr. Eccles' method for audio-frequency oscillations is as follows:

A steel tuning fork has two electromagnets placed in contiguity to its prongs. A triode valve has one electromagnet coil in its grid circuit and the other in its plate circuit and they operate in the following way. When the fork is started in vibration and one prong approaches the iron core of the electromagnet it creates in the coil an electromotive force which causes the grid to become either positively or negatively charged. This then causes an increase or decrease in the plate current and it attracts or repels the other prong of the fork. If the connections are made the right way this action tends to keep the fork in vibration and to increase the amplitude.

Now the fork has a perfectly definite rate of vibration assuming it is kept at a constant temperature and the fork therefore controls the rate of the valve oscillations. The oscillations in the plate circuit can be transferred by means of a coupling transformer to any other circuit and if need be can be amplified so as to give a perfectly constant frequency in any alternating current required for research purposes. In the above case the fork can give vibrations within the range of audition but in some cases electric vibrations are required of a much higher frequency called supersonic. These can be controlled by employing the longitudinal vibrations of a steel rod instead of a fork clamped in the centre.

In those cases in which a still higher frequency is required we can make use of the piezo-electric properties of a quartz crystal. Certain crystals, viz., tourmaline, rochelle-salt and quartz have the property that when compressed along a certain axis an electric polarity develops along another direction. Quartz occurs in hexagonal or six-sided prisms. The longitudinal or symmetric axis is called the optic or Z-axis. The three Y-axes which are normal to the Z-axis and to the faces of the prism are the electric axes and there are three X-axes. If a rectangular slice is cut perpendicular to a Y-axis and its face parallel to an X-axis then if such a slice is compressed in one direction it will exhibit electric

charges in a direction at right angles. In that direction the crystal can also be set in stationary mechanical vibrations and corresponding to these there will be electrical charges produced on the faces of the slice. If then such a slice of quartz is placed between metal plates but is free to expand and contract and if the condenser so formed is coupled in between the grid and plate circuit of a triode in the right direction a tuned electric circuit having capacity and inductance with high tension battery in series inserted in the external filament-to-plate circuit and the grid resistance to the filament, electric oscillations will be set up in the quartz plate and mechanical oscillations in the direction at right angles thereto. The rate of these oscillations is fixed by the dimensions and quality of the quartz plate, and its mechanical oscillations create the electrical, and the valve supplies the energy to maintain the electric and therefore the mechanical vibrations. These may be of frequency up to a million or more.

The crystal can be so cut that it has a high or low frequency rate of oscillation. The crystal controlled valve can then be used to keep perfectly constant the oscillations in a valve transmitter as used in wireless telegraphy.

Also the mechanical vibrations of the quartz generate supersonic air or sound waves, the properties of which have been carefully studied by G. W. Pierce and others.

The piezo-electric qualities of quartz plates cut in the proper direction from quartz crystals was investigated as far back as 1922 by Professor Cady in the United States, who described his researches to the Institute of Radio Engineers, U. S. A. Professor Pierce placed his work on record in the *Proceedings of the American Academy of Arts and Sciences* in 1923. Other exhaustive researches were made by D. W. Dye in 1923 and 1926 at the National Physical Laboratory, England, and other investigators have been G. W. N. Cobbold and A. E. Underdown in 1928 and J. E. P. Vigoureux in 1929 and by these investigators the action of a valve-maintained quartz oscillator has been carefully examined and described. A tuning-fork controlled thermionic valve is employed at the Rugby Wireless Station of the British Postal Telegraph Service to maintain constancy in the carrier wave frequency.

Other interesting applications of the thermionic valve in

research are in the construction of instruments for measuring small high frequency voltages, currents, and powers. The defect of all alternating current instruments depending on the heating power of the current is that as this heating varies as the square of the current the scale readings decrease more rapidly than the current.

Amongst such thermionic valve instruments may be mentioned the Moulin Voltmeter which enables the peak voltage and mean value of an alternating current of any wave-form to be measured by the same instrument. Mr. E. B. Moulin described this instrument in August 1928 in the *Journal of the Institution of Electrical Engineers*, Vol. 66, p. 886, 1928. It consists of a thermionic valve with filament heated by a 4-volt storage battery and the terminals to which the tested alternating voltage is applied connected to the grid and filament respectively of the valve, one through a high resistance shunted by a condenser for grid connection, and a direct reading microammeter for the filament connection. This instrument has the great virtue of absorbing little or no power. It is made in various forms by The Cambridge Instrument Company of England.

A very ingenious application of the three- or two-electrode valve has been made by Dr. H. E. M. Barlow in the construction of a valve ammeter for the measurement of small alternating currents of radio frequency. (See *Journal of the Institution of Electrical Engineers* of London for March 1925. Paper first received in February 1924.)

He constructs a Wheatstone's Bridge circuit two arms of which are formed of the interspace filament-to-grid or filament-to-plate of two thermionic valves. The other two arms are suitable resistances and a suitable microammeter is put in the bridge circuit and a high tension battery supplies current as usual to the circuits. A balance can then be obtained. The filaments of the valves are rendered incandescent by a suitable E.M.F. with a highly inductive coil in series. If then a small alternating current is superimposed on the direct filament heating current of one valve it upsets the bridge balance and causes a deflection of the microammeter.

It is then possible to calibrate the instrument so that the

readings of the bridge ammeter give the strength of the alternating current added to the direct heating current of one valve and such calibration is valid for all frequencies.

It is made to give full scale deflections for A.C. currents of 5, 10, 20, or 30 milliamperes. Dr. Barlow has also made a useful arrangement of two electrode valves for measuring very small condenser capacities.

A thermionic wattmeter has also been devised by Dr. E. Mallett in which two thermionic valves and a differential galvanometer are employed. But instruments of this type in which two valves of quite identical characteristics and a differential galvanometer are requisite are not very likely to come into any general use for commercial purposes.

The application shows however the extensive possibilities of the thermionic valve as an instrument for scientific research outside of and beyond its technical applications and general employment as an amplifier of voltage.